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Air cooling of a horizon-tally grooved turbine blade model with covering metal sleeve.

Jennings, J. C.

University of Minnesota

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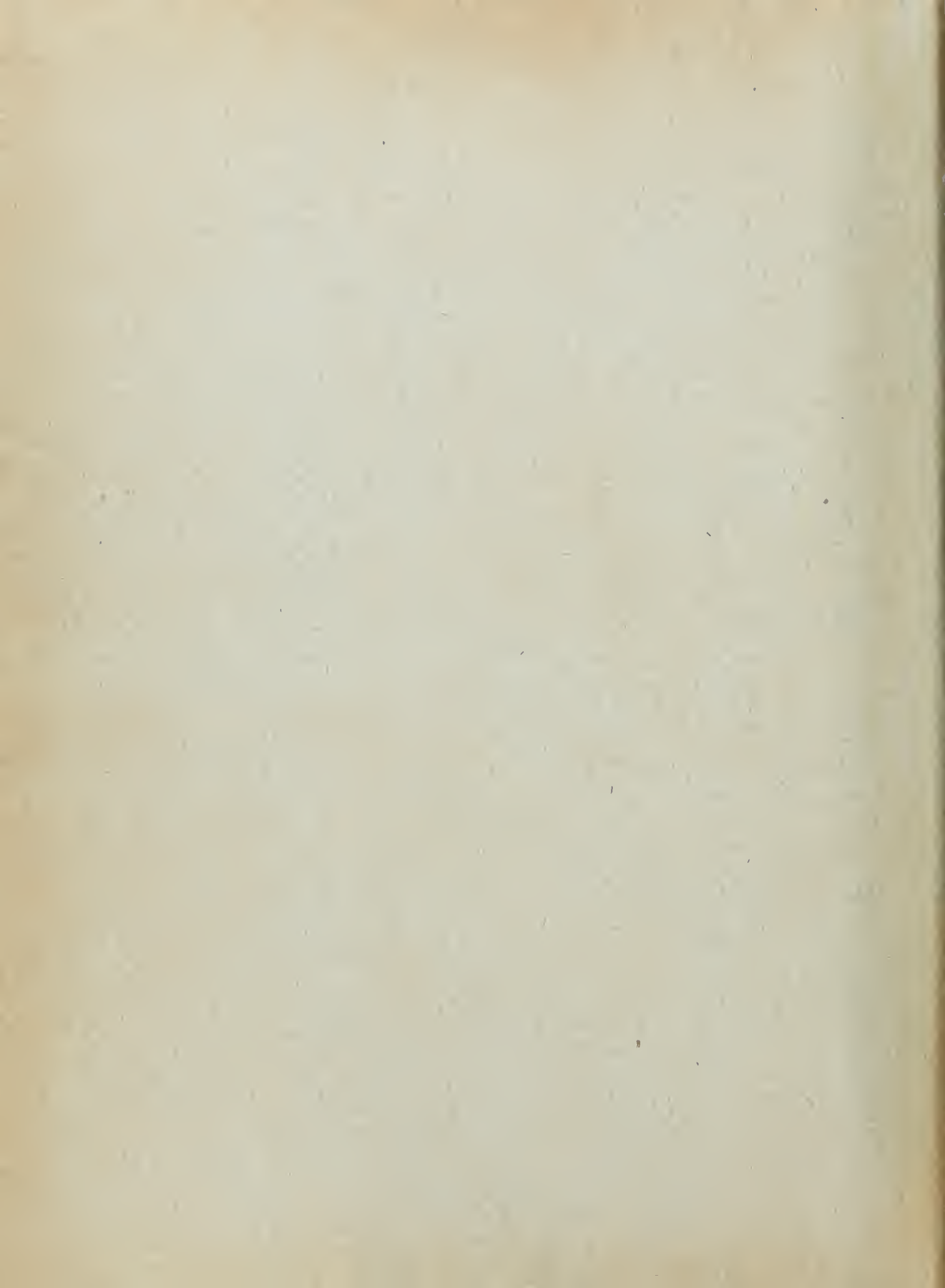
Jennings

Air cooling of a horizontally grooved  
turbine blade model with covering metal  
sleeve.

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AIR COOLING OF A HORIZONTALLY GROOVED  
TURBINE BLADE MODEL WITH COVERING METAL SLEEVE

Submitted to the Graduate Faculty  
of the  
University of Minnesota

by  
J. C. Jennings  
Lt. U.S.N.

In Partial Fulfillment of the Requirements  
for the  
Degree of Master of Science  
in  
Aeronautical Engineering

August 1951



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Personnel of the Aeronautical Engineering and Mechanical Engineering laboratories for their efforts and advice in the construction of the test blade, and their unfailing aid and co-operation in the numberless instances when they were called upon to help with the project.



# MEMORANDUM

The subject herein is a report on the progress of the following project: to develop a new type of machine for the production of paper.

The project was initiated by the Department of Mechanical Engineering, for the purpose of developing a new type of machine for the production of paper.

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## SUMMARY

A static test on a particular air-cooled turbine blade model was conducted at the University of Minnesota in July, 1951. The blade model utilized cooling air which was ducted into the blade near the leading edge, thence into horizontal, or chordwise, grooves between the blade and a thin metal sleeve attached to lands on the blade. Cooling air was discharged at the trailing edge of the blade, where an opening was provided in the sleeve.

Mach numbers in the flow around the test blade were from .4 to .5 with tests being made at gas temperatures at about 800° F., 1000° F., 1200° F., and 1420° F.

The following conclusions were reached:

1. At gas temperatures of about 1420° F., a temperature reduction of 630° F. was experienced near the trailing edge, and a reduction of 890° F. was found near the leading edge, for a cooling air flow rate comparable to 1.67% of combustion air.
2. The blade configuration tested possessed excellent cooling characteristics and showed an economy of

A series of tests were conducted in which the reaction of the metal with oxygen was studied. The results show that the reaction is very rapid at low temperatures and becomes slower as the temperature increases. The reaction is also affected by the surface area of the metal and the pressure of the oxygen.

The following table gives the results of the tests conducted at different temperatures and pressures.

# Table I. Results of tests conducted at different temperatures and pressures.

1. At a temperature of about 100°C, the reaction was very rapid and the metal was completely oxidized in a few minutes. The reaction was also very rapid at a pressure of 1 atm.

2. The reaction was slower at a temperature of about 200°C. The reaction was also slower at a pressure of 2 atm.

cooling air use compared to available data on other cooling configurations.

3. Greater temperature reductions were found at high gas temperatures than at low gas temperatures, with constant rate of cooling air flow. The rate of increase of temperature reduction with gas temperature increase appeared to be linear over the range tested.





## INTRODUCTION

The broad problem in the field of gas turbine operation, with respect to turbine blades, is that of developing a blade capable of withstanding high stresses in a region of high temperatures. Since there are today many hundreds of turbines operating, it is evident that some success has been met in this development.

There is very little which can be done to reduce the stresses associated with the centrifugal forces of the high speed turbine. It is also highly desirable to operate these turbines at the highest permissible limits of temperature. Therefore, cooling of the turbine blades by some outside means has been under considerable investigation recently, as a method of permitting higher turbine gas temperatures. Some of the advantages which may accrue from effective blade cooling are increased power, prolonged blade life, and use of less critical and expensive materials in blade construction.

This report describes the static test of a turbine blade model which was designed to give high economy of cooling air by using the air as a protective layer between the blade body and a covering metal sleeve.



## I DESCRIPTION OF TEST BLADE AND EQUIPMENT

Fig. (1) shows a sketch of the turbine blade model, and Fig. (14) shows a photograph of the blade with the covering metal sleeve attached. The blade was machined from mild steel. No attempt was made to give a twist to the blade, and for simplicity of lathe machining, the air-foil surface was formed of two circular arcs filleted as seen in Fig. (1). The grooves are .025 inches deep; the sleeve is .033 inch rolled black iron sheet. The materials used were chosen because of their ready availability and machinability. The sleeve was formed around the blade, and attached with counter-sunk rivets and screws, which were ground off to be flush with the surface. Total surface area of the blade was 33.8 sq. in. Blade height was  $4\frac{1}{2}$  inches.

Eleven holes for iron - constantan thermocouples were drilled about one-third of the depth of the blade. Only seven of these positions were employed in the tests.

Great care was exercised in drilling the small one-sixteenth inch holes from the leading edge to the main

# 1. DESCRIPTION OF THE TESTS AND RESULTS

The tests were conducted in the laboratory of the Department of Civil Engineering, University of California, Berkeley, California. The tests were conducted on a test rig which was designed to simulate the conditions of a ship's hull in a fluid medium. The test rig consisted of a large tank of water, a model of the ship's hull, and a system of pumps and pipes to circulate the water. The model of the ship's hull was made of aluminum and was 1/10th scale of the actual ship. The water was circulated at a rate of 1000 gpm. The tests were conducted at a Reynolds number of 10^6. The results of the tests are shown in Table 1. The results show that the resistance of the ship's hull increases with the square of the velocity. The resistance of the ship's hull is also affected by the shape of the hull. The results show that a hull with a sharp bow has a lower resistance than a hull with a blunt bow. The results also show that a hull with a smooth surface has a lower resistance than a hull with a rough surface.

The tests were conducted on a test rig which was designed to simulate the conditions of a ship's hull in a fluid medium. The test rig consisted of a large tank of water, a model of the ship's hull, and a system of pumps and pipes to circulate the water. The model of the ship's hull was made of aluminum and was 1/10th scale of the actual ship. The water was circulated at a rate of 1000 gpm. The tests were conducted at a Reynolds number of 10^6. The results of the tests are shown in Table 1. The results show that the resistance of the ship's hull increases with the square of the velocity. The resistance of the ship's hull is also affected by the shape of the hull. The results show that a hull with a sharp bow has a lower resistance than a hull with a blunt bow. The results also show that a hull with a smooth surface has a lower resistance than a hull with a rough surface.



cooling air duct, for misalignment of these holes could cause maldistribution of cooling air to the grooves on each surface.

The test section contained two uncooled blades similar to the test blade, and is shown schematically in Fig. (2). A photograph of this section is given in Fig. (13). The test blade was mounted on a pedestal arrangement to allow its easy insertion into the test section between the two uncooled blades. The blades, with the surfaces of the test section, formed a cascade, making the flow turn an angle of about sixty-four degrees. Each uncooled blade had a thermocouple installed near its leading edge.

The tests were run in an especially designed Gas Turbine Test Cell in the Mechanical Engineering building of the University of Minnesota. The photograph of Fig. (12) shows the control panel, and Fig. (11) shows the test cell interior. There was a Lycoming Model O-435-T air cooled engine, rated at 162 HP at 2800 RPM driving an air compressor, which was a 7.48 : 1 gear ratio supercharger from an Allison V-1710 aircraft engine. The air delivered by the supercharger to the large manifold was ducted to the com-





bustion chamber of a single Allison J33-A-17 turbojet engine burner. Combustion was started by a spark-ignited acetylene flame, and combustion temperatures were controlled by the burner fuel pump bypass, for regulating fuel flow, and by the Lycoming engine throttle, which determined engine RPM, hence supercharger flow rate. Number one diesel fuel was used in the combustion chamber.

The test blade was located in the test section about eleven and one-half inches downstream of the combustion chamber exit.

All thermocouples used were iron - constantan, and were read on a Brown Recording Potentiometer having a scale from 0 - 1600° F.

Cooling air was supplied from the compressed air system of the Mechanical Engineering building. Pumping capacity of the system was greater than the maximum flow rate used, and the supply was available at all times between 80 and 100 psig. Cooling air flow rate was determined from a Fischer and Porter "Flowrator" with a tube size # 5A-25. Cooling air initial temperature was measured by thermocouple.

1. The first step in the process of identifying a problem is to define the problem. This involves identifying the symptoms of the problem and determining the scope of the problem. Once the problem has been defined, the next step is to identify the causes of the problem. This involves identifying the factors that are contributing to the problem and determining the underlying causes. Once the causes have been identified, the next step is to develop a plan of action. This involves identifying the steps that need to be taken to solve the problem and determining the resources that will be needed to implement the plan. Finally, the last step in the process is to implement the plan and monitor the results. This involves putting the plan into action and tracking the progress of the solution. Once the problem has been solved, the final step is to evaluate the results and determine if the solution was effective. This involves comparing the results of the solution to the original problem and determining if the problem has been solved. If the problem has not been solved, the process may need to be repeated.

The New York was damaged in the third battle.

1991-1992

24-25. Cooling air (initial temperature was reduced by  
from 2 inches and lower "temperature" with a 1/2 inch  
from 50 and 100 psi. Cooling air flow rate was controlled  
rate used, and the weight was available at all times de-  
capacity of the system was greater than the system flow  
system of the industrial plant was being tested. Cooling  
cooling air was supplied from the compressed air

Air flow to the burner was measured at an orifice on the intake side of the engine-driven compressor. The orifice was 5.6 inches diameter, in a circular duct eight inches in diameter. Static pressure taps were installed one diameter upstream and one-half diameter downstream of the orifice.

Fuel flow to the burner was measured on a fuel "Flowrator" tube # 5A-60, mounted on the control panel.

Temperature and pressure were measured in the test section four and one-half inches upstream of the test blades. A total pressure tube and a static pressure tap were employed, and a shielded total temperature probe housed an iron - constantan thermocouple. This temperature probe read consistently lower than the uncooled blades of the test section, however, so it was considered of value only as a "reference" temperature. At a constant burner air flow, any desired temperature could be obtained and held constant with  $\pm 5^{\circ}$  F. on this "reference" probe by controlling the burner fuel flow.

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1. The first step is to identify the problem or question that needs to be answered. This involves understanding the context and the specific requirements of the task.

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## II TEST PROCEDURE

Test procedure was simple. Reference temperatures of 800° F., 1000° F., 1200° F., and 1420° F. were successively obtained on the shielded temperature probe. At each reference temperature the flow of cooling air was varied, and readings were taken of all instrumentation as shown in Table I. Great care was exercised in order that equilibrium be reached with each new rate of cooling air flow before readings were taken. A curve is shown in Fig. (7) for a temperature-time check on thermocouple #5 at reference temperature of 1420° F., and the final point of this curve agrees with the reading taken at the beginning of that series of runs, showing that the procedure used was satisfactory.



1. THE RESULTS

The results of the tests are given in the following tables. The first table gives the results of the tests of the 1000 lb. and 1500 lb. test specimens. It will be seen that the results are in good agreement with the theoretical values. The second table gives the results of the tests of the 1000 lb. and 1500 lb. test specimens. It will be seen that the results are in good agreement with the theoretical values. The third table gives the results of the tests of the 1000 lb. and 1500 lb. test specimens. It will be seen that the results are in good agreement with the theoretical values. The fourth table gives the results of the tests of the 1000 lb. and 1500 lb. test specimens. It will be seen that the results are in good agreement with the theoretical values. The fifth table gives the results of the tests of the 1000 lb. and 1500 lb. test specimens. It will be seen that the results are in good agreement with the theoretical values. The sixth table gives the results of the tests of the 1000 lb. and 1500 lb. test specimens. It will be seen that the results are in good agreement with the theoretical values. The seventh table gives the results of the tests of the 1000 lb. and 1500 lb. test specimens. It will be seen that the results are in good agreement with the theoretical values. The eighth table gives the results of the tests of the 1000 lb. and 1500 lb. test specimens. It will be seen that the results are in good agreement with the theoretical values. The ninth table gives the results of the tests of the 1000 lb. and 1500 lb. test specimens. It will be seen that the results are in good agreement with the theoretical values. The tenth table gives the results of the tests of the 1000 lb. and 1500 lb. test specimens. It will be seen that the results are in good agreement with the theoretical values.

### III DISCUSSION OF RESULTS

#### (a) Results of the present investigation

The data are tabulated in Table I. Figs. (3), (4), (5), and (6) show plots of the recorded temperatures of all thermocouples on the test blade vs the weight rate of cooling air flow as determined from the "Flowrator", and represent graphically the results of the tests. It may be noted from the figures that at each reference temperature there was a marked blade temperature reduction for each thermocouple location. No thermocouples were located forward of the main cooling air duct because of space limitations. Thermocouples #1 and #2 consistently read very nearly the same temperature; a natural result since they were both near the duct of incoming cooling air. Temperatures of the points on the concave side of the blade (even numbered points) read slightly lower than those on the convex side, possibly because of greater resistance to flow in the longer grooves of the convex side, which may have caused less cooling air to flow in those grooves.

The distribution of temperature along the blade finds the hottest part at the trailing edge, the coolest

Fig. 1. The same as in Fig. 2, but for  $\alpha = 0.1$ .

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The distribution of *Desmoulinia* along the slide

100-443887-100

part at the incoming air duct near the leading edge, with a maximum temperature difference between hot and cool points of 300° F. The temperature of the cooling air rose as it was heated in its passage along the grooves.

Thermocouple #5 was chosen as a representative point for comparison of temperature reductions at different air flows and uncooled temperatures, for it represents a point removed from the great cooling near the leading edge, and is near the hotter point of the trailing edge. Fig. (8) shows a plot of temperature reduction vs cooling air flow for this thermocouple at various reference temperatures of the hot gases. It was found that temperature reduction increased with flow rate of cooling air, but that after a point, the rate of this increase was small.

An interesting cross-plot of Fig. (8) is shown in Fig. (9) as a set of curves of temperature reduction vs uncooled temperature, for the various rates of cooling air flow. This cross-plot shows that for the region of the tests the temperature reduction at a given weight rate of cooling air flow increased almost linearly with the uncooled temperature. If this linearity holds into regions of higher temperatures, a very rewarding employment of cooling air



part of the boundary air flow near the leading edge and a  
certain temperature difference between the two points  
of 500° F. The temperature of the cooling air flow at it  
was fixed in the process of the process.

Therefore it was shown as a representative  
point for comparison of temperature reduction at different  
air flow and cooling conditions, for it represents a  
point removed from the flow boundary near the leading edge,  
and it was the point of the cooling air flow (Fig. 1).  
When a point of temperature reduction is selected at this  
for this condition (a) below various conditions of  
the hot gases, it was found that temperature reduction in-  
creased with the rate of cooling air, and that after a  
certain rate of this increase was small.

An interesting observation of Fig. 2 is shown in  
Fig. 3) as a way of means of temperature reduction in the  
cooling process, for the various rates of cooling air  
flow. This observation shows that for the region of the  
flow the temperature reduction at a given weight rate of  
cooling air flow increased almost linearly with the increased  
temperature. It also shows that the rate of higher  
temperature, a very small region of cooling air

might be experienced in the neighborhood of 2000° F. and over.

Fig. (10) shows the temperature distribution along the blade at 1420° F. reference temperature, with various rates of cooling air flow. This figure pictures a trend already mentioned - increasing temperatures toward the trailing edge as the cooling air is heated up. The close agreement of the temperatures along the two surfaces is an indication that no major distribution errors in the cooling air flow occurred between the two grooves.

While no data were taken to permit calculation of the sleeve temperature, it was not considered that the sleeve will be a critical part of the blade with regard to temperature, because the amount of blade cooling present makes it obvious that a sizeable heat transfer is going on between the hot gases of combustion and the sleeve; for this condition to occur, there must be a large temperature gradient between these hot gases and the sleeve. Furthermore, in a turbine, the sleeve as constructed would not have to carry centrifugal stress loads as high as the blade body because of its several support lines furnished by the lands.



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along the plate as (1990) (see reference literature) and

1990-1991

Journal of Management Education 33(10) 1139-1154

The following are the results of the study:

slow growth of the population along the two ridges

is an indication that the system is not working properly.

Journal of Interpersonal Violence 26(12)

all our employees are 100% vaccinated and we will be

Leave will be a portion of the sick or personal leave.

System online will be under all circumstances.

Source: U.S. Census Bureau, *Marriage, Divorce, Remarriage in the 1990s*, p. 10.

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*This article is a translation of the original article, which was published in the Russian language in the journal "Voprosy Psichologii" (1997), No. 1, pp. 11-15.*

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There is a significant positive correlation between the number of years of experience and the number of projects completed.

...of the ... ..

(b) Comparison with other investigations

Since the blade model tested was large compared to turbine blades normally used in aircraft engines, a method for comparing the cooling required was considered in order to evaluate the results in terms of other investigations concerned with air-cooled turbine blades for aircraft. The heat flow equation  $Q = hA\Delta T$  was used for this purpose, and the blade size used for comparison was the J33 turbine blade, having an area of about 14.8 sq. in. Test Blade area was 33.8 sq. in.

In the heat flow equation, the variables to be considered were the film heat transfer coefficient, "h", from the hot gases to the sleeve, and the blade area, A. The same  $\Delta T$  was considered for both sizes of blade, and the ratio of heat flows to each blade was estimated. It was assumed that the rate of cooling air flow required would be proportional to the rate of heat flow to the blade sleeve.

$$\text{For the test blade: } Q_1 = h_1 A_1 \Delta T$$

$$\text{For blade of 13.8 sq. in.: } Q_2 = h_2 A_2 \Delta T$$

$$\text{and } Q_1/Q_2 = (h_1/h_2) \times (A_1/A_2)$$



From Ref. (f), page 106, a relation for the film heat transfer coefficient,  $h$ , is given for plane surfaces, and was assumed to hold approximately for the sleeve surface:

$$h = .055 (k/L) (N)^{.75}, \text{ where}$$

$k$  = heat transfer coefficient of the gas  
 $L$  = representative length  
 $N$  = Reynold's number

Substituting the relation for " $h$ " into the expression for heat flow ratio,

$$Q_1/Q_2 = (A_1/A_2) (L_2/L_1) (L_1 L_2)^{.75}$$

A heat flow comparison was made between the test blade and a geometrically similar blade to it, but which had the same area as the J33 blade:

$$Q_1/Q_2 = 2.05$$

It was then assumed that the larger test blade had required 2.05 times as much air for cooling as the smaller blade would have required. There was then a basis for a rough comparison of weight of cooling air to weight of combustion air.

On a J33 engine there are 14 burners of the type





employed in the tests, and there are 54 turbine blades having areas of about 14.8 sq. in. each. So that it was calculated if the 54 blades of the J33 were similar to the test blade, and air-cooled as the test blade; at an engine airflow fourteen times that of the tests, and a temperature of about 1420° F. at the turbine inlet, the cooling conditions found in the test blade would be found in the smaller blades at cooling airflows of .487 those of the test blade.

Using the maximum flow rate of cooling air, 1.204 lb/min, which was employed in the test blade at 1420° F. reference temperature, it was seen that the smaller blades should have been using a total of .528 lb/sec of cooling air, and that the ratio of cooling air weight to combustion air weight would be 1.67%. The temperature reduction would have been the same as for the test blade, according to the preceding calculations.

Care must be taken not to accept the above comparisons as having been proved by these tests. However, the comparisons do indicate that excellent results may be expected by use of the test blade cooling configuration on actual turbine blades.



employed in the study, and there are 22 further classes (the  
the class of about 10% of the total. It is not self-  
contained in the sense of the other classes, but the  
first class, and also the 22 further classes, are all self-  
contained in the sense of the other classes, and a comparison  
of about 10% of the total. The results of the study  
show that the first class is the only one in the study  
which is not self-contained in the sense of the other classes.  
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in the study which is not self-contained in the sense of the other classes.

Table II shows the results of several investigations on air cooling of turbine blade models. It is seen that the blade model of the present investigation shows excellent possibilities with regard to temperature reduction of blade, and weight ratio of cooling air flow to burner air flow.

Table II shows the results of several investigations of the effect of the concentration of the solution on the rate of reaction. It is seen that the rate of reaction increases with increasing concentration of the solution. This is due to the fact that the rate of reaction is proportional to the concentration of the reactants.

The rate of reaction is also affected by the temperature of the solution. As the temperature increases, the rate of reaction increases. This is because the molecules have more kinetic energy and are able to overcome the activation energy barrier more easily. The rate of reaction is also affected by the presence of a catalyst, which lowers the activation energy barrier and increases the rate of reaction.

The rate of reaction is also affected by the surface area of the reactants. A larger surface area increases the rate of reaction because there are more molecules available for reaction. The rate of reaction is also affected by the pressure of the system, which affects the concentration of the reactants.

#### IV CONCLUSIONS

The following conclusions have been drawn from the tests conducted on the horizontally grooved air cooled turbine blade model with covering metal sleeve:

1. At combustion gas temperatures of about  $1420^{\circ}$  F., a temperature reduction of  $630^{\circ}$  F. was experienced near the trailing edge, and a reduction of  $890^{\circ}$  F. was found near the leading edge, for a cooling air flow rate comparable to 1.67% of combustion air.
2. The blade configuration tested possessed excellent cooling characteristics and showed an economy of cooling air use compared to data on other cooling configurations.
3. Greater temperature reductions were found at high gas temperatures than at low gas temperatures, with constant rate of cooling air flow. The rate of increase of temperature reduction with gas temperature increase appeared to be linear over the range tested.

The following conditions were used during the tests:

The test chamber was maintained at a constant temperature of 25°C. The test chamber was maintained at a constant pressure of 1 atm. The test chamber was maintained at a constant humidity of 50%.

1. The test chamber was maintained at a constant temperature of 25°C. The test chamber was maintained at a constant pressure of 1 atm. The test chamber was maintained at a constant humidity of 50%.

2. The test chamber was maintained at a constant temperature of 25°C. The test chamber was maintained at a constant pressure of 1 atm. The test chamber was maintained at a constant humidity of 50%.

3. The test chamber was maintained at a constant temperature of 25°C. The test chamber was maintained at a constant pressure of 1 atm. The test chamber was maintained at a constant humidity of 50%.



TABLE I

TEST DATA AS RECORDED FOR AIR-COOLED TURBINE BLADE  
MODEL HAVING COVERING METAL SLEEVE. TEMPERATURES  
ARE IN DEGREES FARENHEIT AS DETERMINED FROM IRON-  
CONSTANTAN THERMOCOUPLES.

BAROMETER: 29.15 IN. HG. TEMP: 88 °F

| COOLING AIR<br>PRESSURE AT<br>FLOWMETER | COOLING<br>AIR       | TEST SECTION<br>TOTAL<br>PRESSURE | TEST SECTION<br>STATIC<br>PRESSURE | BURNER AIR<br>INTAKE<br>ORIFICE | BURNER<br>FUEL | THERMOCOUPLES IN TEST BLADE |                |                |                |                |                |                |                | UNCOOLED<br>BLADE | UNCOOLED<br>BLADE | "TOTAL" OR<br>REFERENCE<br>TEMPERATURE | BURNER AIR<br>ROOM<br>INTAKE | COOLING AIR<br>AT<br>FLOWMETER |
|---|----------------------|-----------------------------------|------------------------------------|---------------------------------|----------------|-----------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|-------------------|-------------------|--|------------------------------|--------------------------------|
| (GAGE)<br>LB/IN <sup>2</sup>            | FLOWMETER<br>READING | P <sub>0</sub> IN. HG.            | P <sub>s</sub> IN. HG.             | ΔP IN. H <sub>2</sub> O         | LB/HR          | T <sub>1</sub>              | T <sub>2</sub> | T <sub>3</sub> | T <sub>4</sub> | T <sub>5</sub> | T <sub>6</sub> | T <sub>7</sub> | T <sub>8</sub> | T <sub>9</sub>    | T <sub>10</sub>   | T <sub>11</sub>                        | T <sub>12</sub>              |                                |
| 60                                      | 8.05                 | 32.4                              | .4                                 | 15.6                            | 88             | 320                         | 320            | 400            | 390            | 440            | 425            | 450            | 835            | 805               | 800               | 105                                    | 95                           |                                |
| 40                                      | 6.10                 | 32.4                              | .4                                 | 15.6                            | 88             | 370                         | 370            | 450            | 440            | 500            | 480            | 510            | 840            | 810               | 810               | 105                                    | 95                           |                                |
| 20                                      | 4.65                 | 32.3                              | .4                                 | 15.6                            | 89             | 460                         | 465            | 540            | 525            | 595            | 575            | 600            | 840            | 810               | 800               | 105                                    | 95                           |                                |
| 10                                      | 3.51                 | 32.3                              | .4                                 | 15.6                            | 88             | 520                         | 525            | 595            | 575            | 640            | 630            | 650            | 840            | 810               | 800               | 105                                    | 100                          |                                |
| 2.5                                     | 1.82                 | 32.3                              | .4                                 | 15.6                            | 88             | 660                         | 665            | 735            | 690            | 750            | 750            | 775            | 840            | 810               | 800               | 105                                    | 100                          |                                |
| 0                                       | 0                    | 32.3                              | .4                                 | 15.6                            | 87             | 825                         | 825            | 825            | 800            | 820            | 830            | 840            | 840            | 800               | 800               | 105                                    | 100                          |                                |
|   |                      |                                   |                                    |                                 |                |                             |                |                |                |                |                |                |                |                   |                   |  |                              |                                |
| 60                                      | 7.8                  | 32.8                              | .4                                 | 15.6                            | 115            | 400                         | 400            | 500            | 490            | 565            | 540            | 580            | 1035           | 1030              | 1000              | 100                                    | 90                           |                                |
| 40                                      | 6.1                  | 32.8                              | .4                                 | 15.6                            | 115            | 460                         | 465            | 570            | 550            | 640            | 620            | 660            | 1035           | 1030              | 1000              | 100                                    | 90                           |                                |
| 20                                      | 4.65                 | 32.9                              | .4                                 | 15.6                            | 115            | 565                         | 570            | 675            | 650            | 745            | 725            | 770            | 1035           | 1030              | 1000              | 105                                    | 90                           |                                |
| 10                                      | 3.45                 | 32.9                              | .4                                 | 15.6                            | 115            | 680                         | 690            | 780            | 750            | 840            | 835            | 880            | 1040           | 1040              | 1000              | 105                                    | 95                           |                                |
| 2.5                                     | 1.82                 | 32.9                              | .4                                 | 15.6                            | 115            | 840                         | 845            | 920            | 880            | 960            | 950            | 990            | 1045           | 1045              | 1000              | 105                                    | 100                          |                                |
| 0                                       | 0                    | 32.9                              | .4                                 | 15.6                            | 115            | 1020                        | 1020           | 1020           | 995            | 1025           | 1030           | 1050           | 1050           | 1050              | 1000              | 105                                    | 100                          |                                |
|   |                      |                                   |                                    |                                 |                |                             |                |                |                |                |                |                |                |                   |                   |  |                              |                                |
| 60                                      | 7.7                  | 33.5                              | .4                                 | 15.6                            | 146            | 470                         | 475            | 610            | 590            | 695            | 665            | 720            | 1220           | 1250              | 1200              | 105                                    | 85                           |                                |
| 40                                      | 6.0                  | 33.5                              | .4                                 | 15.6                            | 146            | 550                         | 560            | 695            | 670            | 780            | 760            | 810            | 1225           | 1260              | 1200              | 105                                    | 90                           |                                |
| 20                                      | 4.55                 | 33.5                              | .4                                 | 15.6                            | 146            | 680                         | 685            | 825            | 790            | 920            | 890            | 950            | 1230           | 1260              | 1200              | 105                                    | 90                           |                                |
| 10                                      | 3.38                 | 33.5                              | .4                                 | 15.6                            | 146            | 825                         | 830            | 950            | 910            | 1035           | 1020           | 1070           | 1240           | 1275              | 1200              | 105                                    | 90                           |                                |
| 0                                       | 0                    | 33.5                              | .4                                 | 15.6                            | 146            | 1220                        | 1220           | 1220           | 1190           | 1230           | 1230           | 1260           | 1250           | 1290              | 1200              | 105                                    | 90                           |                                |
|   |                      |                                   |                                    |                                 |                |                             |                |                |                |                |                |                |                |                   |                   |  |                              |                                |
| 60                                      | 7.6                  | 34.0                              | .5                                 | 15.6                            | 170            | 530                         | 540            | 710            | 660            | 800            | 770            | 830            | 1395           | 1480              | 1410              | 105                                    | 90                           |                                |
| 40                                      | 5.95                 | 34.0                              | .5                                 | 15.6                            | 170            | 620                         | 625            | 800            | 750            | 895            | 870            | 935            | 1400           | 1490              | 1415              | 105                                    | 90                           |                                |
| 20                                      | 4.35                 | 34.0                              | .5                                 | 15.6                            | 170            | 800/810                     | 810/820        | 980/1000       | 930/945        | 1080/1100      | 1050/1070      | 1120/1130      | 1410           | 1500              | 1420              | 105                                    | 90                           |                                |
| 10                                      | 3.35                 | 34.0                              | .5                                 | 15.6                            | 170            | 970                         | 980            | 1150           | 990            | 1240           | 1210           | 1270           | 1410           | 1490              | 1400              | 105                                    | 95                           |                                |
| 0                                       | 0                    | 34.0                              | .5                                 | 15.6                            | 170            | 1425                        | 1420           | 1420           | 1410           | 1440           | 1430           | 1465           | 1420           | 1500              | 1410              | 105                                    | 95                           |                                |
| 60                                      | 7.6                  | 34.0                              | .5                                 | 15.6                            | 170            |                             |                |                |                | 820            |                |                | 1400           | 1490              | 1420              | 105                                    | 95                           |                                |

TARE = .5 TARE = .15

SMALL TABLE IS TEMPERATURE-TIME  
CHECK ON THERMOCOUPLE # 5 AS  
BLADE WAS COOLED FROM 1440°F TO  
820°F WITH COOLING AIR AT 60 PSIG

| MIN | SEC | T <sub>5</sub> | MIN | SEC | T <sub>5</sub> | MIN | SEC | T <sub>5</sub> | MIN | SEC | T <sub>5</sub> | MIN | SEC | T <sub>5</sub> |
|-----|-----|----------------|-----|-----|----------------|-----|-----|----------------|-----|-----|----------------|-----|-----|----------------|
| 0   |     | 1380           |     |     |                |     |     |                |     |     |                |     |     |                |
| 15  |     | 1330           | 1   | 15  | 1080           | 2   | 15  | 920            | 3   | 15  | 850            | 4   | 15  | 820            |
| 30  |     | 1270           | 1   | 30  | 1030           | 2   | 30  | 890            | 3   | 30  | 840            | 4   | 30  | 820            |
| 45  |     | 1230           | 1   | 45  | 990            | 2   | 45  | 870            | 3   | 45  | 835            | 4   | 45  | 820            |
| 1   | 0   | 1180           | 2   | 0   | 950            | 3   | 0   | 860            | 4   | 0   | 830            | 5   | 0   | 820            |





TABLE II  
COMPARISON OF RESULTS OBTAINED BY SEVERAL INVESTIGATIONS OF AIR-COOLED TURBINE BLADES

| Investigator  | Ref.                | Configuration  | Gas Temp.     | Blade Temp. Reduction<br>or Hot Cases<br>Permissible Temp. Increase | Cooling<br>Air, %<br>Total wt |
|---------------|---------------------|--|---------------|---|-------------------------------|
| NACA          | Ref. (a)            | Hollow Blade   | Not Specified | Permissible Temp. Increase<br>580° F.                               | 16.0%                         |
| NACA          | Ref. (a)            | Blade with Insert  | Not Specified | Permissible Temp. Increase<br>790° F.                               | 5.5%                          |
| Kohlmann      | Ref. (b)            | Hollow Blade   | 1592° F.      | Blade Temp. Reduction<br>289° F.                                    | 10.0%                         |
| Mildahn       | Ref. (c)            | Cooling Jets (Boundary Layer)<br>Film Cooling, Holes and<br>Slot in Leading Edge | 1500° F.      | (Limited area)<br>390° F.   | .53 lb/min                    |
| Ness          | Ref. (d)            | Ceramic Sleeve   | 1500° F.      | 140° F. to 285° F.  | .9 lb/min                     |
| Dressendorfer | Ref. (e)<br>Present | Air cooled   | 1600° F.      | 875° F.   | .9 lb/min                     |
| Jennings      | Report              | Grooved Blade, Metal Sleeve  | 1460° F.      | 640° F. to 900° F.  | 1.67%                         |

[illegible]

TABLE III  
PRESSURE MEASUREMENTS IN TEST SECTION FOR CONFIRMATION OF MACH NUMBER

| $T_{11}^{\circ}F.$ | $P_{11}$ Hg | Fuel Flow | $T_0^{\circ}F.$ | $P_s$ in Hg | $P_0$ in Hg | Barom. in Hg | $P_E/P_0$ |
|--------------------|-------------|-----------|-----------------|-------------|-------------|--------------|-----------|
| 80                 | 15.6        | 0         | 142.0           | 0.0         | 1.3         | 29.07        | .961      |
| 80                 | 15.6        | 86        | 800             | 0.0         | 2.9         | 29.07        | .911      |
| 80                 | 15.6        | 112       | 1000            | 0.0         | 3.4         | 29.07        | .896      |
| 80                 | 15.6        | 138       | 1200            | 0.0         | 3.9         | 29.07        | .883      |
| 80                 | 15.6        | 168       | 1420            | 0.0         | 4.5         | 29.07        | .866      |





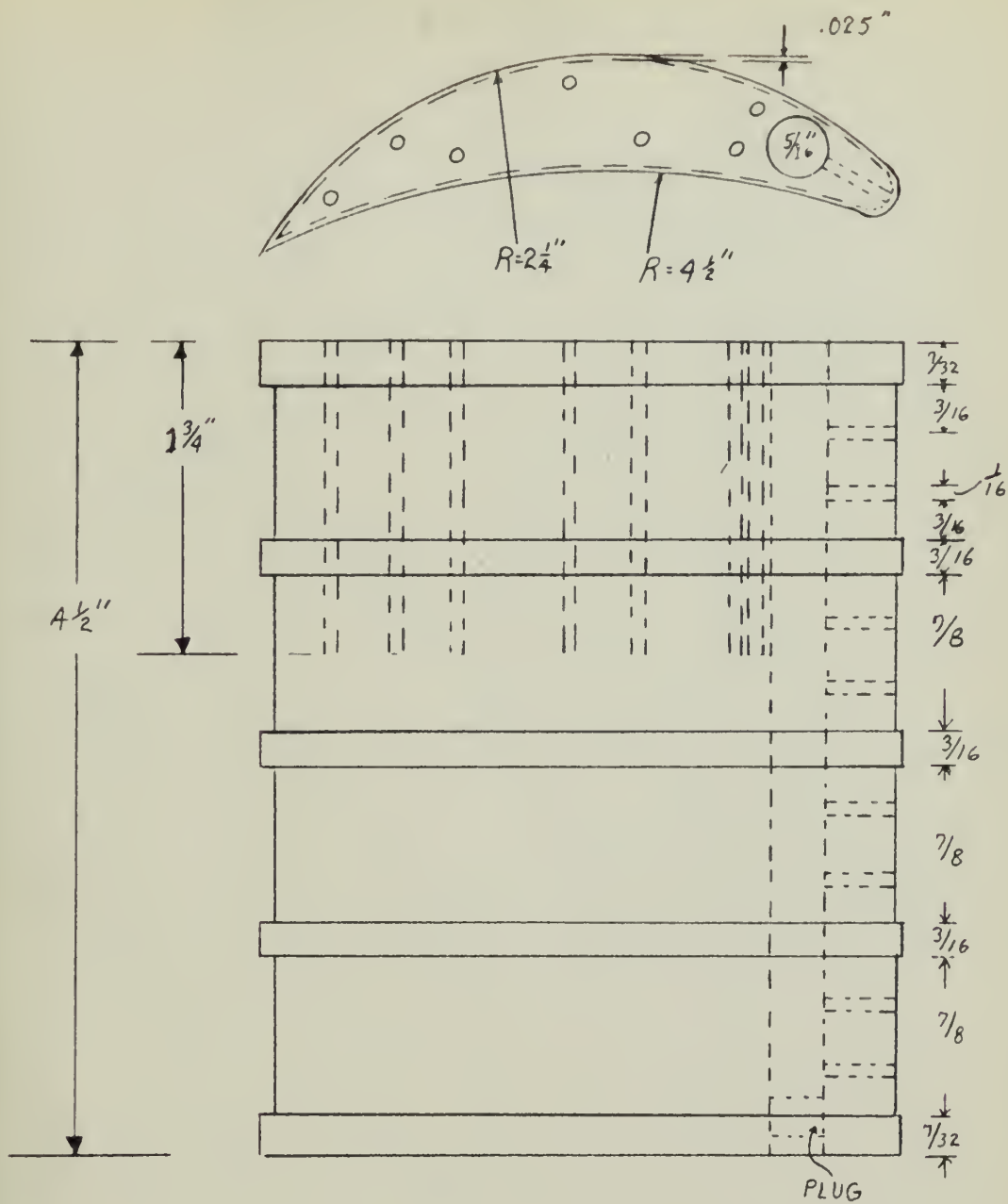


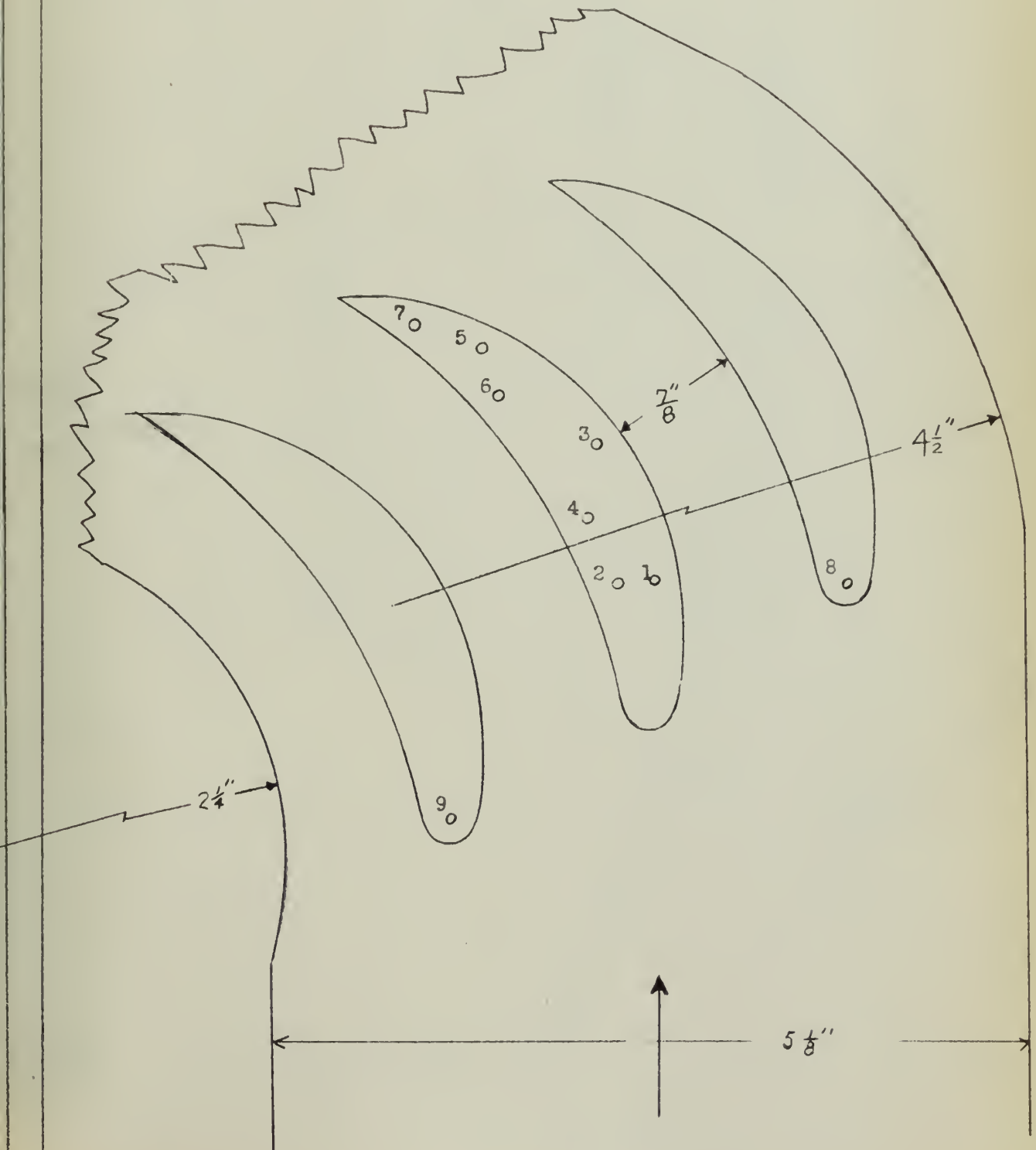
Fig. 1

Sketch of Body of Grooved Turbine Blade Model



Fig. 2

Line Sketch of Test Section Showing Static  
Test Cascade and Location of Thermocouples





1600

1400

1200

1000

Temperature, °F

800

600

400

200

0

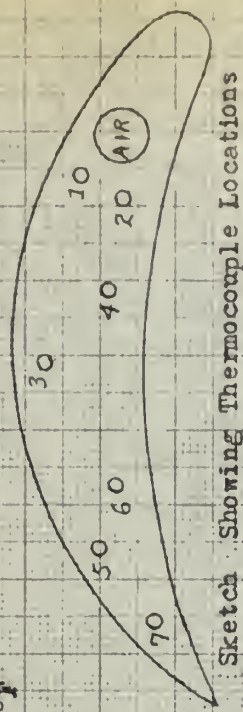
0 .1 .2 .3 .4 .5 .6 .7 .8 .9 10 11 12 13

Cooling Air Flow, Pounds per Minute

Fig. 3

Curves Showing Variation of Temperature  
with Rate of Cooling Air Flow for Air-  
cooled Turbine Blade Model at Seven  
Thermocouple Locations.

Reference Temperature : 800 °F



Sketch Showing Thermocouple Locations

Thermocouple # 1 and # 2

Thermocouple # 3

Thermocouple # 4

Thermocouple # 5

Thermocouple # 6

Thermocouple # 7

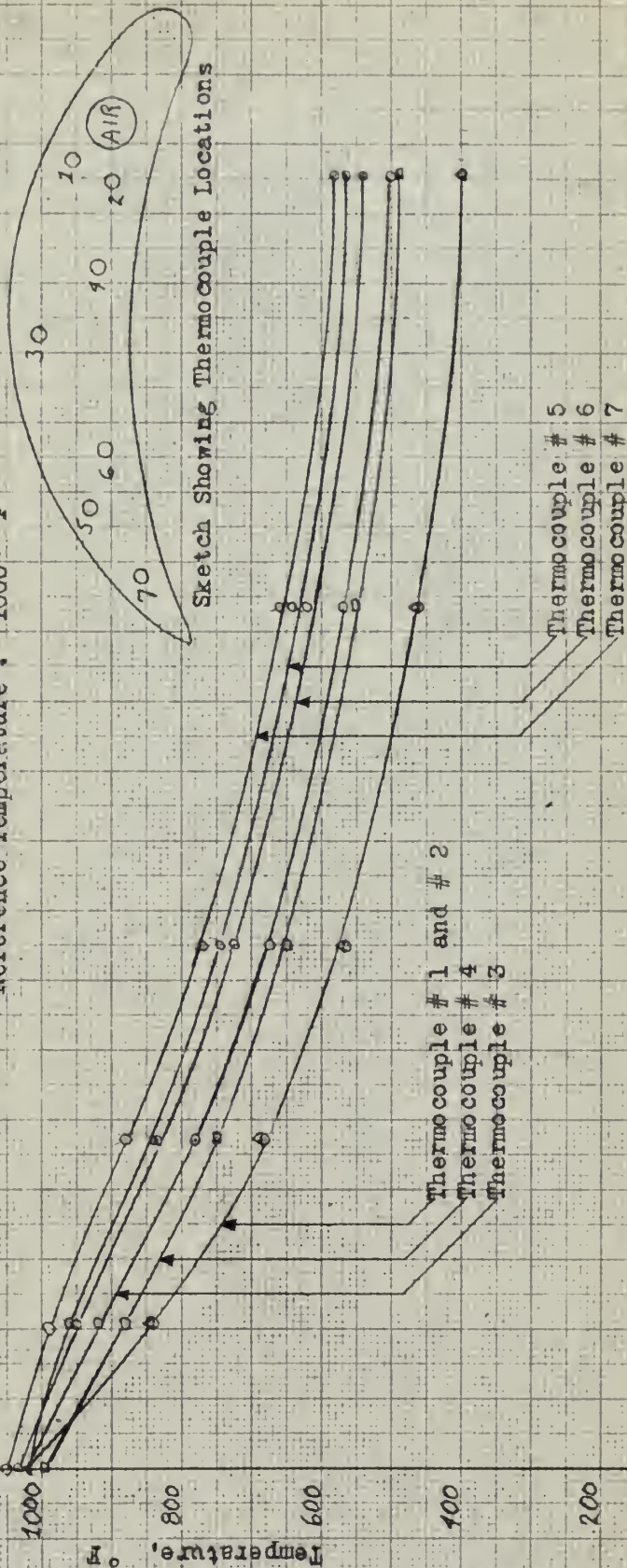




Fig. 4

Curves Showing Variation of Temperature  
with Rate of Cooling Air Flow for Air-  
cooled Turbine Blade Model at Seven  
Thermocouple Locations.

Reference Temperature : 1000 °F



Cooling Air Flow, Pounds per Minute





Fig. 5

Curves Showing Variation of Temperature  
with Rate of Cooling Air Flow for Air-  
cooled Turbine Blade Model at Seven  
Thermocouple Locations.

Reference Temperature: 1200 °F

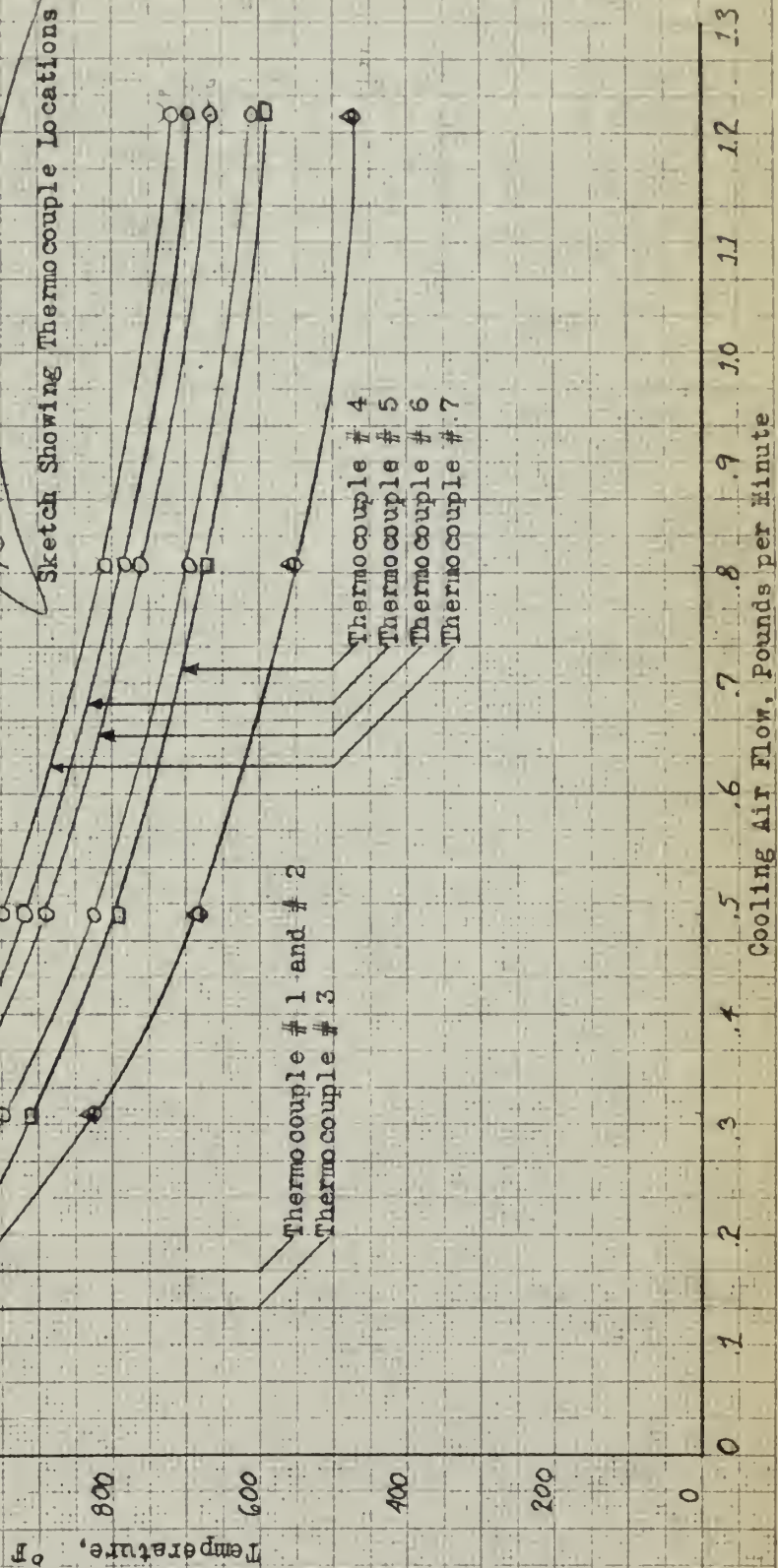
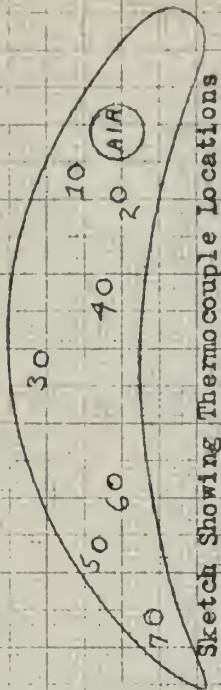


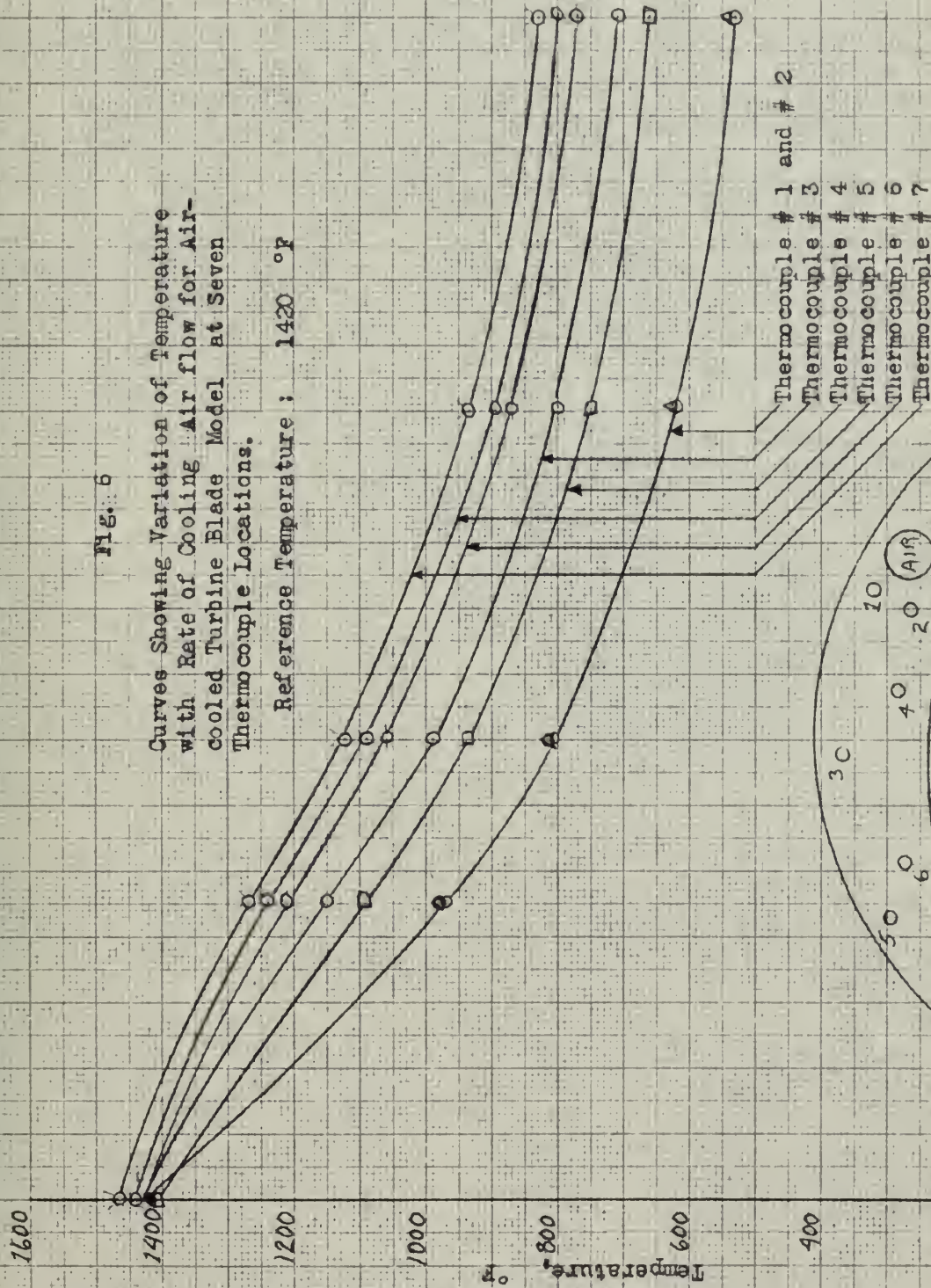




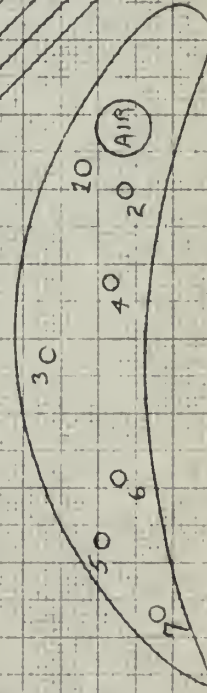
Fig. 6

Curves Showing Variation of Temperature  
with Rate of Cooling Air flow for Air-  
cooled Turbine Blade Model at Seven  
Thermocouple Locations.

Reference Temperature : 1420 °F



Sketch Showing Thermocouple Locations



Cooling Air Flow, Pounds per Minute





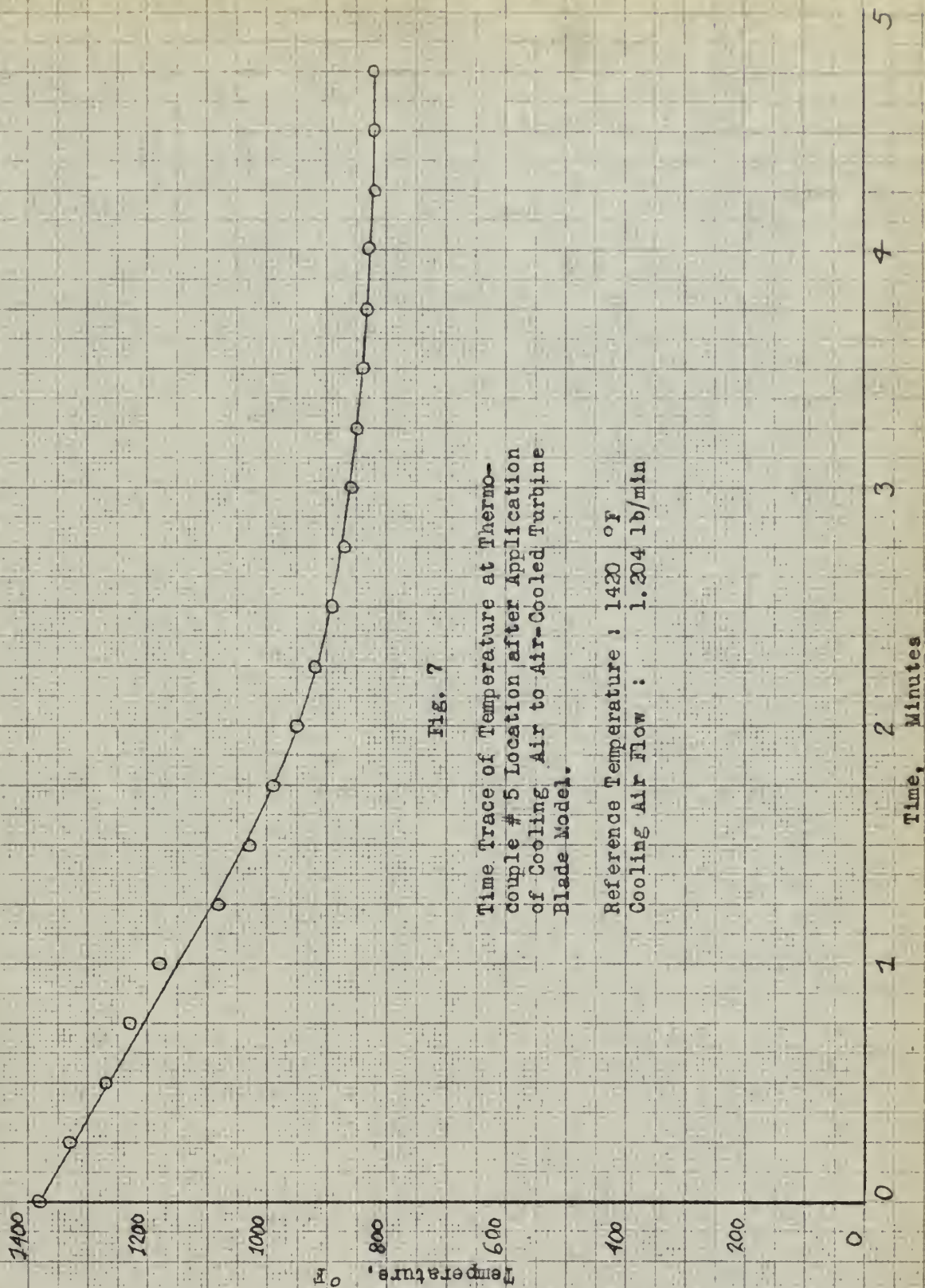


Fig. 7

Time Trace of Temperature at Thermo-couple # 5 Location after Application of Cooling Air to Air-Cooled Turbine Blade Model.

Reference Temperature : 1420 °F  
Cooling Air Flow : 1.204 lb/min



Fig. 8

Curves of Temperature Reduction vs  
Rate of Cooling Air Flow for Design-  
ated Thermocouples and Reference  
Temperatures.

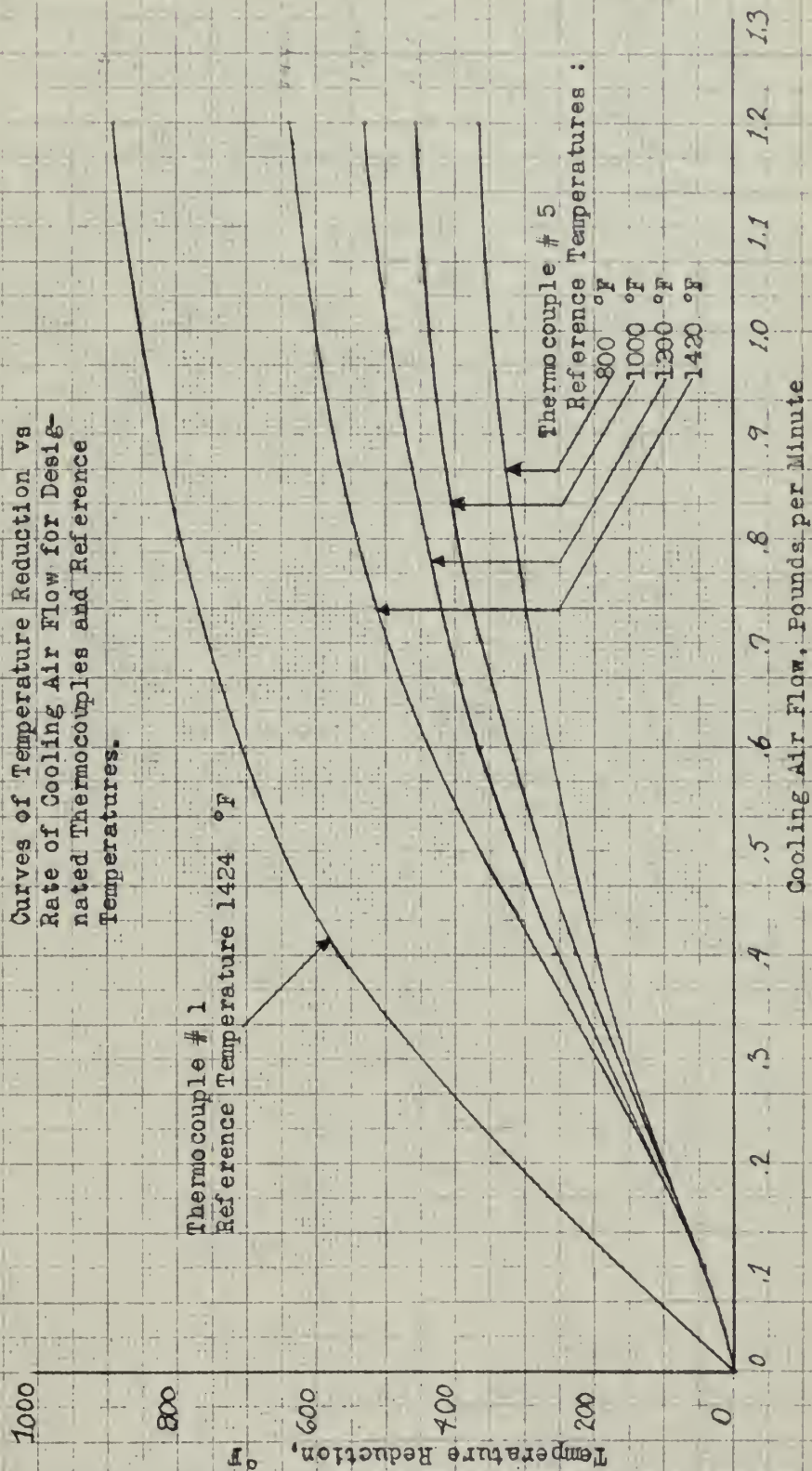






Fig. 9

Curves of Temperature Reduction vs  
Uncooled Temperature for thermocouple  
# 5, at Various Rates of Cooling Air Flow.

Cooling Air Flow:

1.2 lb/min

.8 lb/min

.6 lb/min

.4 lb/min

Uncooled Temperature, °F

1000

800

600

400

200

0

0

200

400

600

800

1000

1200

1400

1600

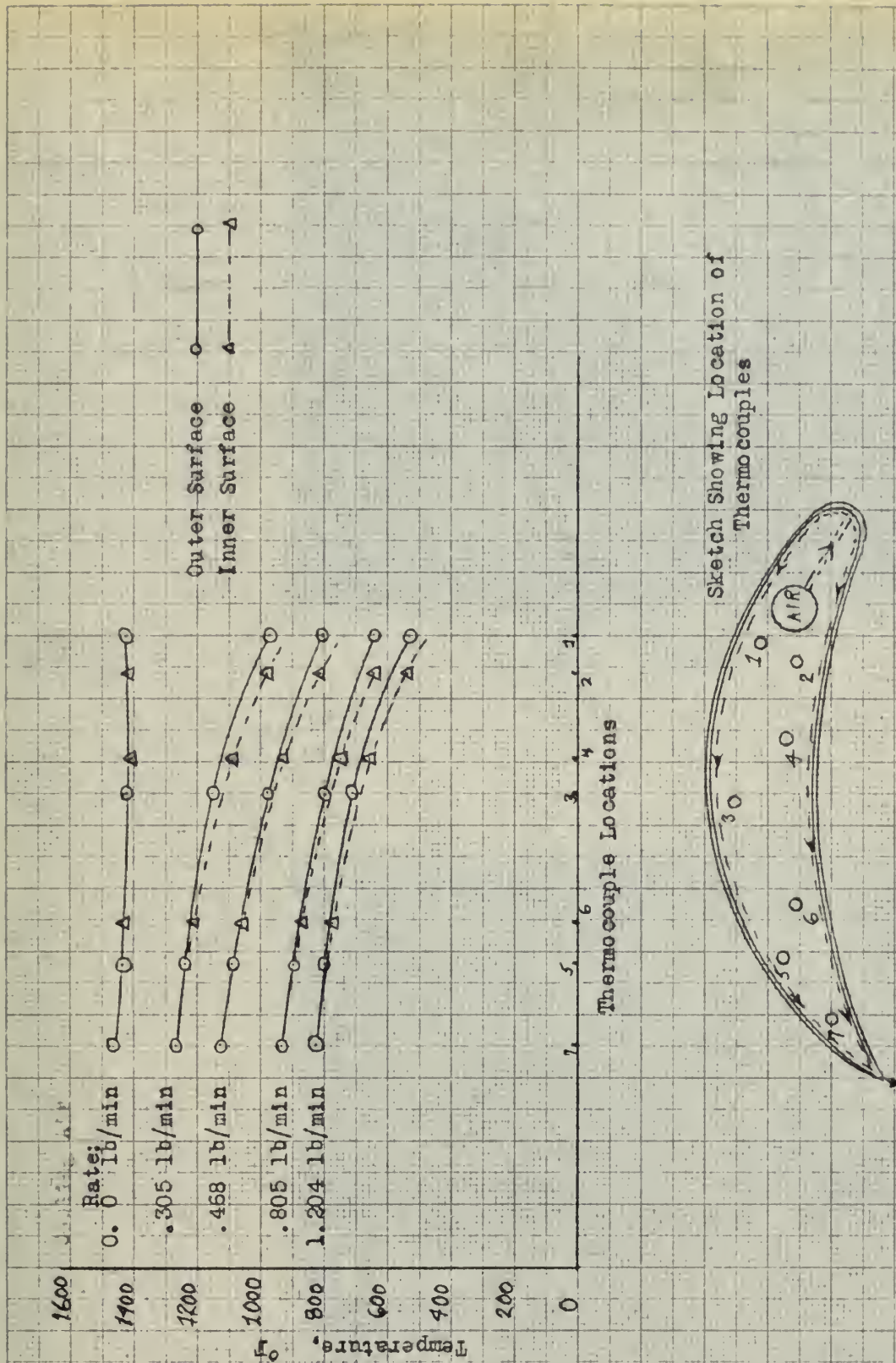
1800

2000

Temperature Reduction, °F







Sketch Showing Location of Thermocouples

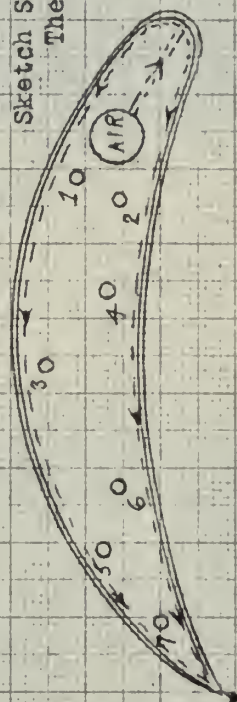


FIG. 10

Curves Showing Chordwise Temperature Distribution for Outer and Inner Surfaces of Air-cooled Turbine Blade Model with Various Rates of Cooling Air Flow. Reference Temperature: 1420 °F





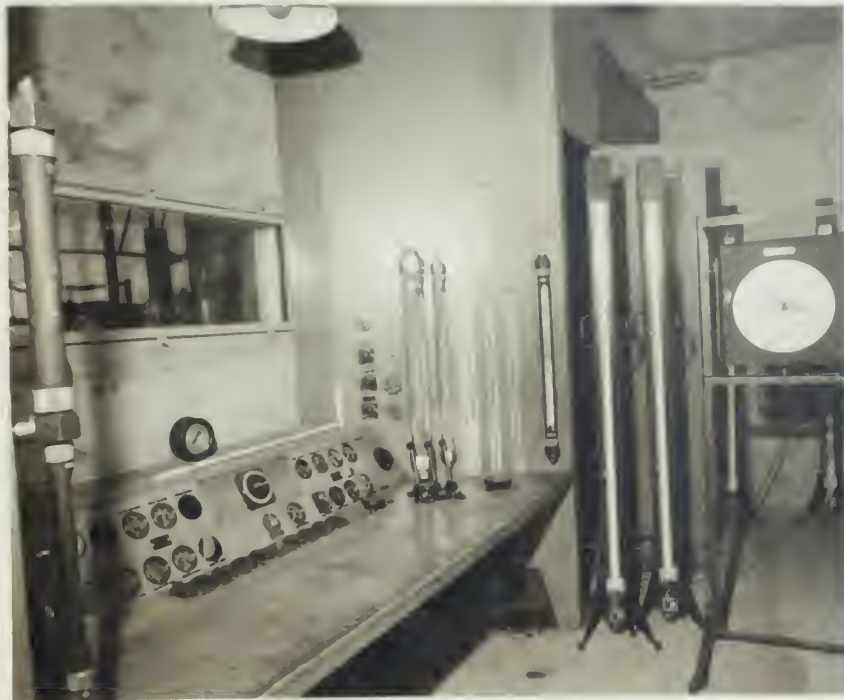


FIG. 12  
CONTROL PANEL

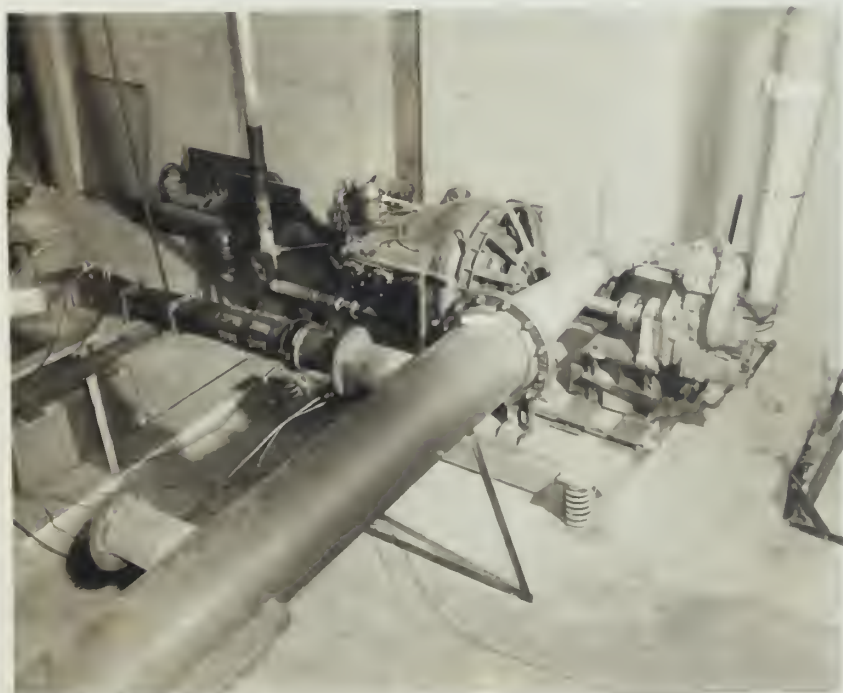


FIG. 11  
TEST CELL





FIG 13  
TEST SECTION



FIG. 14  
HORIZONTALLY GROOVED AIR COOLED TURBINE  
BLADE MODEL WITH COVERING METAL SLEEVE



#### APPENDIX

The Mach Number in the Test Section ahead of the blades and in the flow about the blades was desired for reference purposes. Measurements of  $P_s$  and  $P_o$  in the test section were expected to give this information through the  $P_s/P_o$  ratio in the gas tables, interpolated for a gamma of 1.33 of the combustion gases.

The mass flow (neglecting weight of fuel) determined from the inlet orifice should also provide a check on Mach number in the test section by application of  $w = \rho AV$ , where  $\rho$  and  $A$  were values at the test section.

Comparison of Mach Numbers determined by the two methods did not show agreement, so the run of Table III was made to check pressure values. The Machs as determined from this second table still did not agree with the Machs as determined from the mass flow for the runs. Cause of disagreement was sought.

All pressure leads had been thoroughly checked for leaks before attachment to the test section. It is noted that total pressure agrees with measurements taken in the



### APPENDIX III

The bank number in the test section ahead of the

blades and in the flow about the blades was checked for

reference purposes. Measurements of  $\frac{1}{2}A$  and  $\frac{1}{2}B$  in the test

section were expected to give data indicating through the

$\frac{1}{2}A \frac{1}{2}B$  ratio in the gas turbine, determined for a range of

1.50 of the combustion gases.

The same flow (neglecting weight of fuel) deter-

mined from the inlet orifice should also provide a check

on bank number in the test section by application of

$w = \frac{1}{2}A \frac{1}{2}B$ , where  $\frac{1}{2}A$  and  $\frac{1}{2}B$  were values at the test section.

Comparison of bank number determined by the two

methods did not show agreement; as the case of Table III was

used to check pressure values. The bank number determined

from this second table will did not agree with the bank

number determined from the case flow for the same. Cause of

disagreement was sought.

All pressure heads had been thoroughly checked

for leaks before attachment to the test section. It is noted

that total pressure agrees with measurements taken in the

first set of runs. Static pressure agreed -- but this agreement was at zero reading. It is considered that static pressure should have increased somewhat as fuel flow increased -- it was therefore decided that the  $P_s$  reading was in error, and that a leak must have occurred at the point of attachment. No pressure check for leaks was made at this point because of its position within the test section.

Further consideration showed that in view of the apparent dependability of the total pressure readings the  $P_s$  could be determined by simultaneous solution of the mass flow relations and the pressure ratio relations for the Mach Number in the Test Section. This solution was performed graphically, and the results given below:

| $T_0$    | Mach Number at Test Section | Mach Number Around Blades |
|----------|-----------------------------|---------------------------|
| 800° F.  | .265                        | .400                      |
| 1000° F. | .284                        | .435                      |
| 1200° F. | .293                        | .460                      |
| 1420° F. | .314                        | .49                       |

Mach Number around the blades was determined from the area relation of the test section cross section (23 sq. in.) to the area presented for flow in the cascade (15.75 sq. in.).

first set of runs. These pressure agreed -- for this reason  
 that was an error reading. It is considered that this  
 pressure should have been about 100 lb. per sq. in.  
 instead -- it was thought that the 100 lb. per sq. in.  
 was an error, and that a test had been conducted at the  
 point of failure. The pressure above the test was not  
 at this point because of the position which the test was  
 made.

Further investigation showed that in view of the  
 apparent irregularity of the total pressure reading the  
 100 lb. per sq. in. could be determined by a comparison of the  
 time relations and the pressure ratio relations for the  
 test number is the test number. This relation was performed  
 respectively, and the results given below.

100 lb. per sq. in. at test section. Each number is given below.

|      |      |      |
|------|------|------|
| 1000 | 1000 | 1000 |
| 1000 | 1000 | 1000 |
| 1000 | 1000 | 1000 |
| 1000 | 1000 | 1000 |
| 1000 | 1000 | 1000 |

Each number around the table was determined from  
 the time relation of the test section cross section (100 sq.  
 in.) to the area specified for flow in the passage (100 sq.  
 in.).

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- Ref. (c) "The development of a color black for the film 'The Great Escape', by J. L. Smith, M.S. Thesis, University of Minnesota, August 1955.
- Ref. (d) "The development of a color black for the film 'The Great Escape', by J. L. Smith, M.S. Thesis, University of Minnesota, August 1955.
- Ref. (e) "The development of a color black for the film 'The Great Escape', by J. L. Smith, M.S. Thesis, University of Minnesota, August 1955.
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- Ref. (g) "The development of a color black for the film 'The Great Escape', by J. L. Smith, M.S. Thesis, University of Minnesota, August 1955.
- Ref. (h) "The development of a color black for the film 'The Great Escape', by J. L. Smith, M.S. Thesis, University of Minnesota, August 1955.
- Ref. (i) "The development of a color black for the film 'The Great Escape', by J. L. Smith, M.S. Thesis, University of Minnesota, August 1955.
- Ref. (j) "The development of a color black for the film 'The Great Escape', by J. L. Smith, M.S. Thesis, University of Minnesota, August 1955.



## SAMPLE CALCULATIONS :

1. Cooling air flow rate:

$$Q_2 = Q_1 \left( \frac{P_2}{P_1} \right)^{\frac{1}{2}} \left( \frac{T_1}{T_2} \right)^{\frac{1}{2}}$$

"FLOWMETER" equation from instrument handbook.

For the first run at 800°F:

$$Q_2 = 8.05 \text{ (METER READING)}$$

$$P_2 = 14.7 \text{ psia (METER CALIBRATION)}$$

$$P_1 = (60 + 14.32) = 74.32 \text{ psia}$$

$$T_2 = 560^\circ \text{R (METER CALIBRATION)}$$

$$T_1 = (75 + 460) = 535^\circ \text{R (COOLING AIR)}$$

$$Q_1 = 8.05 \left( \frac{74.32}{14.7} \right)^{\frac{1}{2}} \left( \frac{560}{535} \right)^{\frac{1}{2}} = 18.0 \text{ ft}^3/\text{min}$$

@ 100°F, 14.7 psia

$$W = \rho Q = (.071)(18) = \underline{1.278} \text{ lb/min}$$

2. BURNER AIR FLOW : Ref. (3)

$w = .668 A_2 K \sqrt{P_1 \Delta P}$ , which for the orifice used reduces to

$$w = 2.52 \sqrt{\frac{P \Delta h_w}{T}} \text{ lb/sec}$$

$P$  = Barometer, inches of mercury

$T$  = Room intake temperature, °R

$\Delta h_w$  = Orifice pressure drop, inches of water

$w$  = Air flow rate, lb/sec

$$w = 2.52 \sqrt{\frac{29.15 \times 15.6}{565}} \text{ lb/sec}$$

$$w = \underline{2.26} \text{ lb/sec}$$







Thesis  
J47

Jennings

16269

Air cooling of a horizontally grooved turbine blade model with covering metal sleeve.

DEC 2  
NOV 23

7  
4564

Thesis  
J47 Jennings

16260

Air cooling of a horizontally grooved turbine blade model with covering metal sleeve

DEC 2  
NOV 23

7  
4564

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Air cooling of a horizontally grooved turbine blade model with covering metal sleeve.



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